Novel Multiplexing Technique for Detector and Mixer Arrays

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Future space submillimeter telescopes will require large-format (many 1000's of elements) imaging detector arrays to perform state-of-the-art astronomical observations. A crucial issue related to a focal plane array is a readout scheme which is compatible with large numbers of cryogenic detectors elements. When the number of elements becomes of the order of thousands the electrical layout for individual readout amplifiers becomes nearly impossible. Another important concern is about the large number of wires leading to a 0.1-0.3 K platform. In the case of TES, a scheme for time-division multiplexing of SQUID read-out amplifiers has been recently demonstrated [1]. In this scheme the number of SQUIDs is as many as the number of the detectors (N) but only one SQUID is turned on at a time. The SQUIDs are connected in series in columns so the number of wires leading to the amplifiers can be reduced, but it is still of the order of N. Another approach [2] uses a frequency domain multiplexing of the bolometer array. The bolometers are biased with ac currents whose frequencies are individual for each element and are much higher than the bolometer bandwidth. The output signals are connected in series in a summing loop which is coupled to a single SQUID amplifier. The total number of channels depends on the ratio between the SQUID bandwidth and the bolometer bandwidth and can be at least 100 according to the authors.

We propose a novel solution for large format arrays based on the Hadamard transform coding technique which requires only one amplifier to read out the entire array of potentially many 1000s elements and uses ~ 10 wires between the cold stage and room temperature electronics. This can significantly reduce the complexity of the readout circuits.

As an example of the technique, we consider a possible implementation using four transition-edge sensors (TES) and a SQUID amplifier. The electrical diagram is shown in Fig. 1. All detectors are individually voltage biased and the signal currents are summed in the input coil of a SQUID amplifier. In order to de-convolve the individual signals S1-S4 from the total reading, four consequent readings are performed. Every time a different polarity pattern is applied to the detector bias (shown in Fig.1). The mathematical basis for the de-convolution procedure uses the Hadamard Transform (HT) and the corresponding voltage polarity patterns are given by the Walsh-Hadamard functions [3]. A very good description of the HT algorithm and its applications for imaging and spectroscopy can be found, e.g., in [4].

The Walsh-Hadamard functions are binary functions (plus and minus ones) and for our purpose they correspond to positive and negative biases across detectors. This assumes the detector current-voltage (IV) characteristic is a symmetrical one that is true for bolometers. For four elements the Hadamard Transform is given by a simple vector Eq. 1

$$\mathbf{R} = \frac{1}{4}\mathbf{H}_4 \bullet \mathbf{S}, \mathbf{S} = \mathbf{H}_4 \bullet \mathbf{R}. \tag{1}$$

Here **R** and **S** are 4-element vectors of readings and signals correspondingly. $\mathbf{H}_4$ is the corresponding Hadamard matrix (see Eq. 2).

$$\mathbf{H}_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \tag{2}$$

The Hadamard matrix is especially simple if its order (same as the number of detector elements) is 1, 2, 4, 8, 16, 32, … . The higher order matrices are all based on the basic 2×2 matrix:

$$\mathbf{H}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \mathbf{H}_4 = \begin{bmatrix} \mathbf{H}_2 & \mathbf{H}_2 \\ \mathbf{H}_2 & -\mathbf{H}_2 \end{bmatrix}, \mathbf{H}_{2N} = \begin{bmatrix} \mathbf{H}_N & \mathbf{H}_N \\ \mathbf{H}_N & -\mathbf{H}_N \end{bmatrix}. \tag{3}$$

Examples of different order matrices can be found in [3,4]

Beside the major advantage of using just one amplifier, this technique allows to improve signal-to-noise ratio (SNR) of the measurements. Indeed, during a single reading event 4 signals are algebraically added whereas the electrical noises from individual detectors, i_noise_n, (which are obviously independent) are totaled as $I\_noise = \sqrt{\sum_n i\_noise_n^2}$. The average SNR improvement for the aforementioned technique is $N^{1/2}$ [4].

The HT based multiplexing can be applied to the detectors with asymmetrical IV characteristic. In this case, instead of flipping the polarity one has to turn the bias on and off. A somewhat different set of electrical "masks" consisting of 0's and 1's needs to be used in this case (S-matrix, in terminology of Ref. 4). For the above example of the H-matrices the correspondent S-matrices can be easily generated: **S** = (**H**+**I**)/2 (**I** is the unity matrix). The SNR improvement is somewhat worse in this case: $(N+1)/2\sqrt{N} \approx \sqrt{N}/2$ (for large N) [4]. The technique based on S-matrix can be applied to arrays of mixers. However, the problem of feeding many high frequency IF signals into one amplifier is definitely more severe than that for slow detectors.

The HT multiplexing technique has been known in optical imaging and spectroscopy for many years. However, the implementation of the masks was strictly mechanical For example, a coded mask technique has been used in some X-ray telescopes to record an image using a single detector and a set of masks with transparent and opaque segments. The sequence of segments should have fulfilled the aforementioned mathematical ordering sequence (e.g., that of Eq. 3). Since the encoding in this case occurs on the optical side of the detector system, the modification of the SNR is different from what we expect in our electrical scheme [4]. In optical multiplexing the optical noises are not necessarily independent and after the de-convolution can be redistributed in such a way that the SNR in a pixel with a weak useful signal can become smaller. As a result, despite on the potential average increase of the SNR, the contrast of the image can degrade. It cannot happen for the scheme which we propose. Our multiplexing occurs on the "electrical" side of the detector system after all optical signals (useful one and noises) are already detected. The SNR improvement takes place due to suppression of the electrical noise at the detectors output. The optical noise appears after the de-convolution as a part of the optical signal and its rejection is matter of the following data interpretation.

As usual, the strong advantage of the Hadamard Transform based multiplexing technique does not come for free. There are at least two problems which can hamper the use of this technique. Generation of N electrical masks would certainly take time especially when N is of the order of thousands. Figure 2 illustrates the time diagram which should be expected in bolometers. The time necessary to hold a certain voltage across a detector must be at least τ (the bolometer time constant). This allows to accumulate the energy of the signal in a bolometer. So the total time required to obtain one image would be $N\tau$ that may be unacceptably long for some slow bolometers. The problem relaxes if the bolometers are fast. For example, if we consider a hot-electron direct detector (HEDD) which is a recently proposed micron-size version of TES [5], the intrinsic time constant given by the electron-phonon relaxation time can be $\approx$ 1ms [6]. A typical for TES modification of the time constant due to the electro-thermal feedback mechanism would reduce it to 30-100 μs. In this case even a 10^4-element array can be read out during ~ 1 sec.

The second problem is a generation of the electrical polarity masks. If the masks are generated outside of the dewar then the described technique does not have any advantage for reduction of the heat loading. One would need to run $2N$ wires to bias the bolometers. However, due to binary nature of Walsh-Hadamard functions and their cyclic properties a better solution might be possible. We envision some sort of a parallel-to-serial converter located on one of cold stages inside the dewar (see Fig. 3). Such a converter would generate a new polarity pattern at N serial outputs every time a new control bit arrives to the input of the converter. It would need just a few wires for bias and control input. The read-out SQUID would typically need 6 wires. A particular design of the converter would depend on the cooling requirements. If the detectors need to be moderately cooled, the converter can be placed on a 4K-stage. In this case, it could use semiconductor transistor technology. For deeper cooling (100 mK), the Josephson logic circuits must probably be used.

We think that the described multiplexing approach would work well together with arrays of HEDD detectors. Beside expected record sensitivity at sub-MM wavelengths [5], the HEDDs can be fabricated on bulk dielectric substrates (Si, sapphire) (see Fig.4). It certainly makes attractive to combine such an array with the on-chip fabricated Walsh-Hadamard function generator. Another advantage, as was mentioned above, is a small time constant which makes the time needed to take one image short enough for most of applications.

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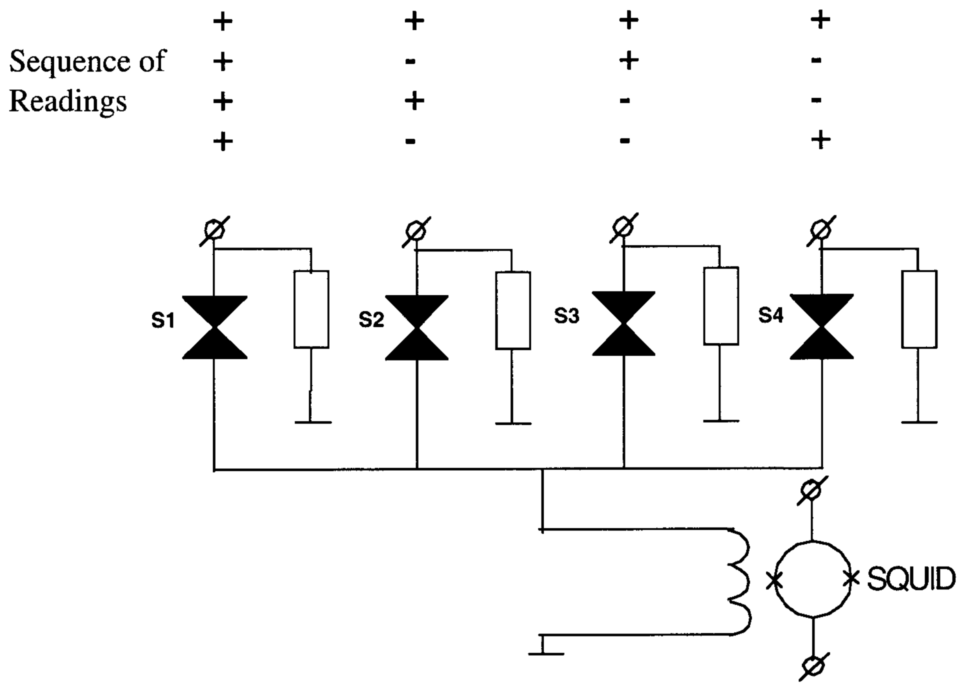


Fig. 1. An electrical circuit for multiplexing of 4 transition-edge sensors. All four detectors are individually voltage biased. Signal currents (S1-S4) from all detectors are summed into a SQUID input coil. The multiplexing is done by applying a sequence of four patterns of bias polarities. The de-convolution of the signal distribution among the detectors is done using the Hadamard Transform algorythm.

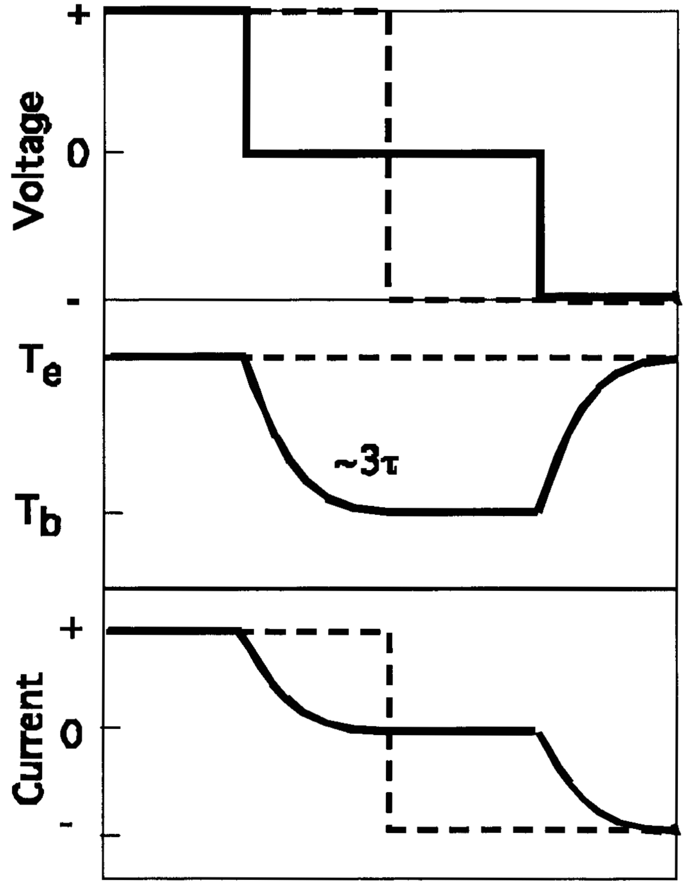


Fig. 2. The time diagram for the polarity switching across a bolometer. If the switching is done fast (dashed line) comparing to the bolometer response time τ, the electron temperature does not "sense" that and remains constant. So, the current just changes its polarity and the device is ready again. The polarity pattern should be held during a period of, at least, τ to let the bolometer to collect the signal energy. If the switching is done slow (soild line) at least two 3τ time lags corresponding to the bolometer cool off and warm up times would add to the signal hold time.

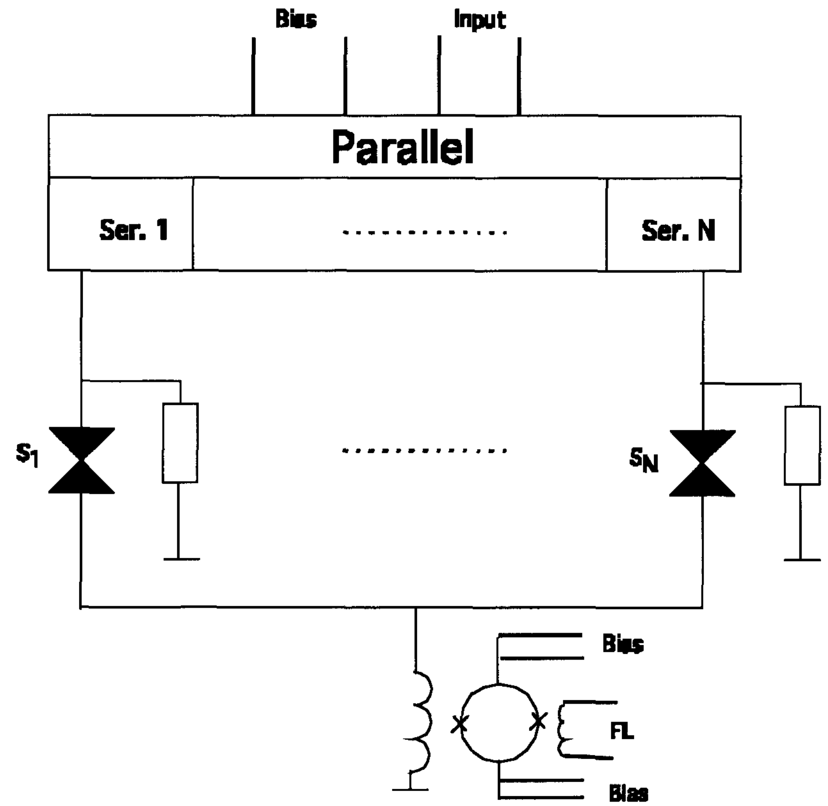
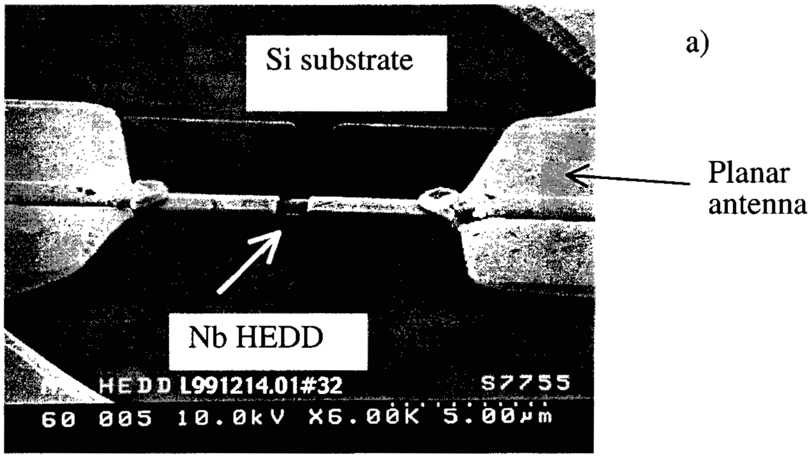


Fig. 3. A hypothetic block-diagram for generating of Walsh-Hadamard electrical bias masks. A parallel-to-serial converter operates as a shift-register receiving one bit at a time that causes generating a next voltage pattern. The converter may need just a few wires for bias and signal input. A SQUID amplifier would need 6 wires: 4 for bias and 2 for feedback loop (FL).



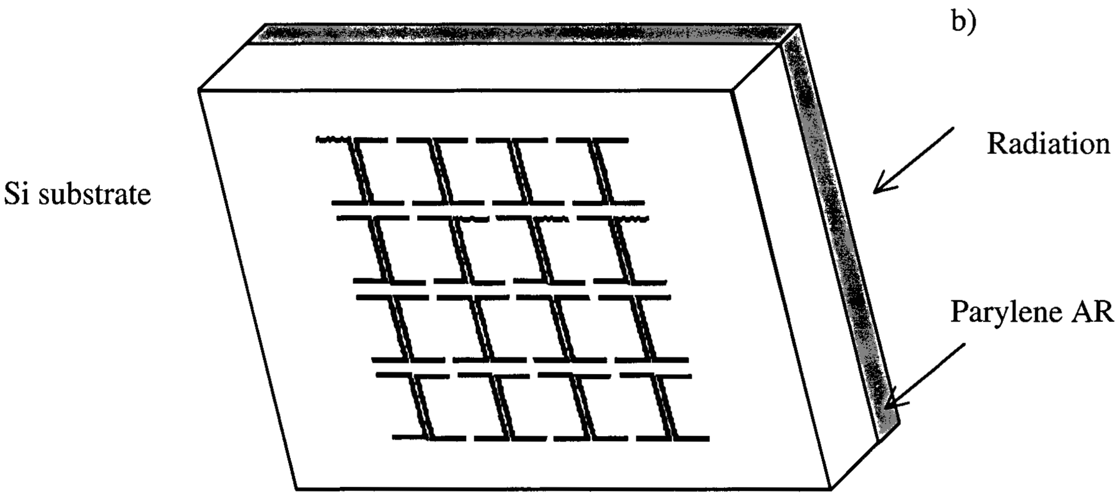


Fig. 4. A monolithic array of antenna-coupled HEDDs for sub-MM wavelengths.
a). an SEM image of a 1×1 μm^2 Nb prototype HEDD on Si substrate. The device is combined with a spiral antenna. The detector was fabricated by H.G. Leduc at JPL.
b). A 4×4 sub-MM array of bolometers. Narrowband antennas will be necessary for lower T_c bolometers. A twin-slot antenna (shown in the figure) is a possible choice since it has a relatively narrow one octave bandwidth. Such antennas have been used up to 2.5 THz [7] for hot-electron superconducting mixers. A parylene anti-reflecting (AR) coatings works well for Si at THz frequencies.